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ABSTRACT

The effective mean free path for antinucleons in nuclear matter is calculated at intermediate energies from the Fermi gas model, in terms of the nucleon-antinucleon total and differential scattering cross sections. The results are used to obtain the imaginary part of the optical-model potential in the formalism of Riesenfeld and Watson.

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* Work done under the auspices of the U. S. Atomic Energy Commission.

† A visitor from the Argentine Army.

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## I. INTRODUCTION

The antiproton beam from the Berkeley Bevatron has been used in many experiments with counters,[1] bubble chambers,[2] and photographic emulsions[3] to study the interaction of antinucleons with nucleons and nuclei.

Since the most successful theoretical approach to the problem of the nucleon-nucleus scattering has been made through the optical model of the nucleus,[4] Glassgold[5] has recently presented a detailed calculation of the antinucleon-nucleus interaction using this formalism. His work has shown that the most important parameter of the problem is the imaginary part of the central optical potential, since its value becomes very large as a result of the large antinucleon-nucleon cross section. Unfortunately, at the time Glassgold made his calculation, neither the $\bar{N}$-N differential scattering cross sections nor the total cross sections were known at the required energies, so that he could not obtain the actual value of the effective cross section. Therefore he chose for the imaginary part of the optical potential two extreme values: one corresponding to the total experimental cross section as measured in Reference 1b at 450 Mev, and the other corresponding to the annihilation part only of this cross section.

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Since, at the energies here considered, these two extreme values differ by a factor of 2, we have considered it advisable to calculate the effect of the Pauli principle in the scattering, using the now known differential cross sections.[6]

In doing this we have chosen for the imaginary central optical potential the standard definition,

$$V_{CI} = \frac{k}{M} \frac{1}{\bar{\lambda}_s} , \qquad (1)$$

where $k$ is the antinucleon momentum in the $\bar{N}$-$N$ barycentric system, $M$ the nucleon mass, and $\bar{\lambda}_s$ the "effective mean free path" defined by

$$\bar{\lambda}_s = \frac{1}{\rho \bar{\sigma}} = \frac{4\pi \lambda^3}{3 \bar{\sigma}} , \qquad (2)$$

where $\bar{\sigma}$ is defined below (Formula (4)), and $\rho$ and $\lambda$ as in Reference 4b.

Within this formalism our problem has been reduced to calculating the "effective $\bar{N}$-$N$ cross section," i.e., the part of the total $\bar{N}$-$N$ cross section not excluded by the Pauli principle.

In order to do that we have followed the ideas of Goldberger[7] and Hayakawa, Kawai, and Kikuchi[8] in their calculations of the same effect in the nucleon-nucleus system. However, there are two main differences between the $\bar{N}$-nucleus and $N$-nucleus interaction. The first is that the Pauli principle applies only to the nucleon inside the nucleus (and not to the incoming antinucleon), and also only to the scattering part of the cross section (the annihilation part is entirely unaffected). The second is that the $\bar{N}$-$N$ differential scattering cross section is strongly peaked in the forward direction owing to diffraction from the annihilation process, thus invalidating the assumption of isotropy of the angular distribution. Also we take an energy dependence of the $\bar{N}$-N scattering cross section as $1\ k$ instead of $1\ k^2$, as chosen by Hayakawa in the N-N case. Therefore we have maintained the picture of the nucleus as a mixture of two noninteracting Fermi gases at zero temperature, but we have dropped the hypothesis of isotropy and have instead used a differential $\bar{N}$-N scattering cross section of the form

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{1}{k}\left[A + B\cos\theta + C\cos^2\theta\right] ,$$

which fits fairly well the theoretical and measured differential cross sections for $\bar{p}$-p and $\bar{p}$-n scattering in the energy range between 100 and 250 Mev. It would be possible to have a better fit with higher powers of cos θ, but the calculation becomes unreasonably complicated. Considering the rough nature of the model, elaborate computations are unjustified.

One difficulty with the Fermi gas model that plays an important part in antinucleon phenomena is the lack of any consideration of the real shape of the nucleus. As we shall see, the interaction of antinucleons with the nucleus is mainly on the nuclear surface, where the density of nucleons is smaller and the Pauli principle less effective. Some consideration of this effect can perhaps be accomplished by using a small value of the Fermi energy. We have chosen 33 Mev for this parameter, corresponding to $\lambda = 1.2 \times 10^{-13}$ cm. A second deficiency of our calculation is that the uniform k dependence of the coefficients of the cos θ expansion of the differential cross section fails to represent the narrowing of the forward diffraction-scattering peak with increasing energy, and therefore underestimates the effect of the Pauli principle at the higher energies. This error is not very important, however.

## II. CALCULATION OF THE "EFFECTIVE MEAN FREE PATH"

Let $\vec{P}_1$ and $\vec{P}_1{}'$ be the antinucleon momenta in the laboratory system, before and after the collision respectively, and $\vec{P}_2$ and $\vec{P}_2{}'$ the corresponding momenta of the target nucleon. The Fermi model gives rise to a uniform distribution of $P_2$ bounded by the Fermi momentum $P_F$, which we assume to have the same value for neutrons and protons. The Pauli principle requires $P_2{}' > P_F$. See Fig. 1.

If we write the differential scattering cross section in the nucleon-antinucleon barycentric system as $\frac{d\sigma}{d\Omega} \mid \vec{P}_1 - \vec{P}_2 \mid = K + L \cos\theta + M \cos^2\theta$, we get for the effective scattering cross section

$$\bar{\sigma}_{scat}(P_1) = \frac{3P_1}{4\pi P_F^3} \int_0^{\infty} (J_1 + J_2 + J_3) dx \quad , \qquad (3)$$

where

$$J_1 = 4\pi^2 K x^2 \left[(1 + x^2 - 2\alpha^2) Z_1 + Z_2\right] \quad ,$$

$$J_2 = -2\pi^2 L x^2 (1 - x^2) \left[Z_1 - (1 + x^2 - 2\alpha^2)^2 Z_3\right] \quad ,$$

$$J_3 = 2\pi^2 M x^2 \left\{\frac{2}{3} Z_2 + (1 + x^2 - 2\alpha^2) Z_1 + (1 - x^2)^2 (1 + x^2 - 2\alpha^2)^3 Z_4 - (1 + x^2 - 2\alpha^2) \left[\frac{1}{3}(1 + x^2 - 2\alpha^2)^2 + (1 - x^2)^2\right] Z_3\right\} \quad ,$$

$$x = \frac{P_2}{P_1}, \qquad \alpha = \frac{P_F}{P_1},$$

$$Z_1 = \frac{1}{x} \sin^{-1} \frac{2x}{1 + x^2},$$

$$Z_2 = 2, \qquad Z_3 = \frac{2}{(1 + x^2)^2 (1 - x^2)}$$

and

$$Z_4 = \frac{2}{3} \frac{3(1 + x^2)^2 - 8x^2}{(1 + x^2)^4 (1 - x^2)^3}.$$

We consider a nucleus with the same number of protons and neutrons and average over the $\bar{p}$-p and $\bar{p}$-n cross sections (the former including charge exchange), therefore defining

$$\bar{\sigma} = \langle \sigma_{annih} \rangle + \langle \bar{\sigma}_{scat} \rangle, \tag{4}$$

where

$$\langle \sigma_{\left\{ \begin{smallmatrix} annih \\ scat \end{smallmatrix} \right\}} \rangle = \sum_{I=0}^{1} \frac{2I + 1}{4} \sigma^{I}_{\left\{ \begin{smallmatrix} annih \\ scat \end{smallmatrix} \right\}} \text{ (I is the isotopic spin).}$$

We now determine $K$, $L$, and $M$ by fitting the averaged theoretical angular distributions of $\bar{p}$-p and $\bar{p}$-n scattering at different energies.[6]

The integration (3) has been made numerically and the results, expressed in terms of the mean free path $\bar{\lambda}_s$, are shown in Fig. 2. For comparison the mean free paths obtained (a) from an isotropic angular distribution (with the same $k$ dependence), and (b) from complete neglect of the exclusion principle, are also plotted.

Finally, Table I shows the imaginary part of the central optical-model potential, according to Formula (1), at several different energies, together with the corresponding values for the case of no Pauli principle effect.

TABLE I

Optical potentials: $V_{CI}$ in Mev ($\lambda = 1.2 \times 10^{-13}$ cm)

| | $E_{lab}$ (in Mev) | | | | |
|---|---|---|---|---|---|
| | 50 | 100 | 140 | 200 | 260 |
| With exclusion principle | 64* | 73 | 77 | 80 | 84 |
| Without exclusion principle | 90 | 103 | 106 | 107 | 108 |

* The value of $\lambda_s$ has been extrapolated.

## III. CONCLUSION

The large value of the nucleon-antinucleon cross section has long been known to imply a very short mean free path for antinucleons in nuclear matter. The exclusion-principle effect considered here increases somewhat the mean free path, but not enough to change the conclusion that nearly all antinucleon interactions occur on the nuclear surface.

In the same energy range the nucleon effective mean free path is larger than $5 \times 10^{-13}$ cm, showing a striking difference between the nucleon-nucleus and antinucleon-nucleus interaction.

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FIGURE CAPTIONS

Fig. 1. Coordinate systems and limits of integration.

Fig. 2. Mean free path of antinucleons in nuclear matter.

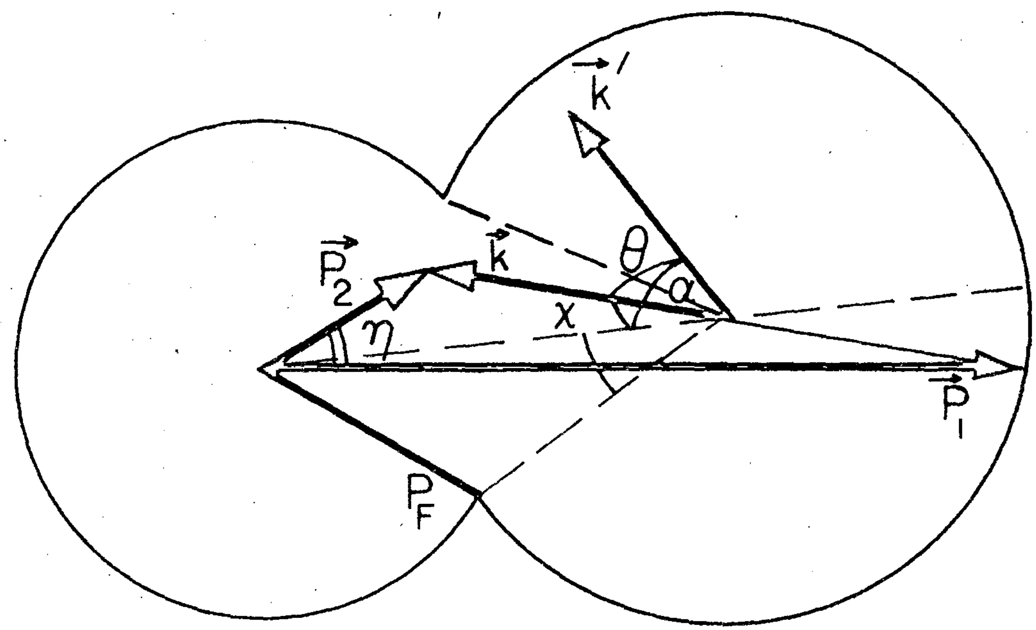


Fig. 1

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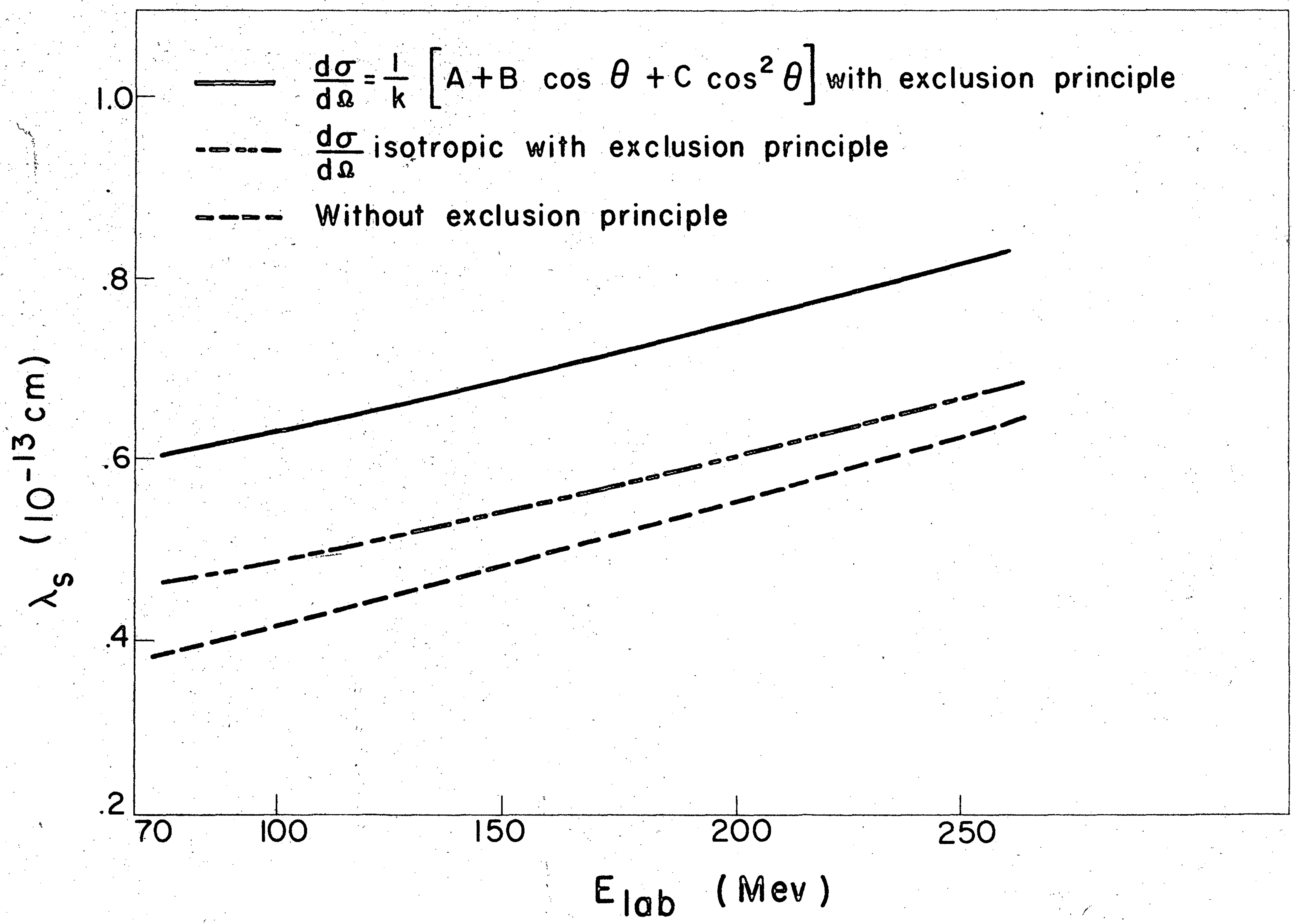

dσ/dΩ = 1/k [A+B cos θ + C cos² θ] with exclusion principle
dσ/dΩ isotropic with exclusion principle
Without exclusion principle
1.0
.8
.6
.4
.2
λs (10⁻¹³ cm)
70
100
150
200
250
E lab (Mev)


MU-6-2

Fig 2